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Energy Policy 30 (2002) 541–552

ENERGY POLICY

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Vintage structure dynamics and climate change policies: the case of US iron and steel

Matthias Ruth*, Anthony Amato

Environmental Policy Program, School of Public Affairs, University of Maryland, Van Munching Hall, College Park, MD 20742, USA

Abstract

The US iron and steel industry consists of two main sectors—integrated firms producing outputs predominantly from virgin materials and fossil fuels, and electric arc furnaces operating mainly on scrap and electricity. Capacity and market shares of the former have declined for more than three decades, leading to reductions in energy use and emissions as the existing capital stock is retired. In contrast, electric arc furnace production not only continues to expand along with its capacity expansions but is also able to adopt advanced technology and improve energy efficiencies and carbon intensities.

This paper investigates implications of changes in the cost of carbon for output, energy use and carbon emission profiles of the two sectors of the industry, and compares the results for different climate change and technology policies. Special attention is given to the dynamics of the industry's capital vintage structure. The analysis indicates that for the case of the US iron and steel industry, an increase in cost of carbon would result in emission reductions by accelerating the shift to electric arc furnaces. The same emissions reductions as those from cost of carbon increases can be achieved by technology-led policies only under the assumption that very sizeable gaps exist between current and possible energy efficiencies for electric arc furnaces and that their existing capital stock can be rapidly turned-over in favor of less carbon intensive technologies.

Keywords: US iron and steel industry; Capital vintage; Embodied technological change; Carbon emissions; Energy efficiency; Climate change policy

1. Introduction

The US iron and steel industry accounts for approximately 9% of manufacturing energy use and 2.3% of all energy used in the USA (Office of Technology Assessment, 2000). Iron and steel production is a significant contributor of carbon emissions because the industry relies heavily on fossil fuels as an energy source, and on limestone for the purification of iron oxides. Several major developments occurred in the structure of the industry, the technologies it is using, and the regulatory and economic environment in which it operates that led to improvements in its energy and emissions profile. Some of these developments are discussed in the following sections. Given recent developments, this study then asks: What are the likely future development paths for the industry if climate change policies are introduced into the picture? We address this question by focusing on the industry's energy use and carbon emissions profiles and quantifying changes in the industry with the help of a dynamic model of the industry that is specified on the basis of econometric analyses and engineering information. Extending past work (Ruth et al., 2000b) this model has been designed to distinguish capital vintage classes and thus has the unique ability to analyze vintage-specific impacts of alternative industrial and climate change policies. These vintage-specific effects are important because

- the ability of industry to respond to policy depends on the longevity of capital units and the age structure of the existing capital stock,
- differences in energy and emissions intensities exist among vintage classes and between vintage classes and newly available capital equipment, and
- production capacity and utilization rates differ by vintage class.

For our analysis, we choose a range of assumptions about future economic and policy conditions to explore likely future energy and emissions profiles of the

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*Corresponding author. Tel.: +1-301-405-6075; fax: +1-301-405-4675.

E-mail address: matthias_ruth@umail.umd.edu (M. Ruth).

0301-4215/02/$ - see front matter
PII: S0301-4215(01)00129-X

industry.[1] The remainder of this paper documents and justifies these assumptions, outlines the structure of the model within which they are used, and presents and compares a set of policy scenarios for the industry. The paper closes with conclusions regarding the effectiveness of various climate change policies.

2. Capital-embodied technical change and vintage effects

In modeling energy-intensive industries, which typically are also capital intensive, special attention needs to be given to the long lead times needed for capacity additions, slow turnover rates and long-lived nature of the capital stock, and the extent to which existing capital is malleable (Jacobi and Wing, 1999). For capital-intensive industries, embodied technological change is often the main driver of changes in input (for example energy) efficiencies while disembodied technological change, such as capital retrofits and learning-by-doing effects, tend to play a secondary role (Jacobsen, 2000). For example, Forsund and Hjalmarsson (1983) find relatively fixed input coefficients for vintage classes within the Swedish cement industry and limited adaptation possibilities for existing capital. In an analysis of the potential for improvements in the US cement industry, Worrell et al. (2000) conclude that capital stock turnover is key to improving the industry's energy efficiency, whereas retrofits to existing capital have limited potential. Consistent with these observations in industrialized nations, Sterner (1990) shows that within the Mexican cement industry 90% of the changes in energy use were due to capital-embodied technological progress.

Capital turnover and improvements of industries with predominantly capital-embodied technological change can suitably be modeled with a capital vintage approach. Specifically, capital vintage models can explicitly account for the production capabilities and input efficiencies of vintage classes and hold these constant or relatively constant throughout the lifetime of the capital equipment. By accounting for the lifetime of capital, the efficiencies of each class, and the composition of production and utilization rates by class, energy use of the industry can be determined. Changes in aggregate energy efficiency of the industry occur as new capital is added, old capital retired, or with changes in utilization rates of existing capital classes.

It is crucial for policymakers to understand the capital vintage dynamics of an industry as those dynamics reflect on the industry's ability to meet policy objectives (Jacobi and Wing, 1999). The inertia that vintage effects create for capital intensive industries may be widespread, and have been noted, for example, by Jacques et al. (2001) in the case of the North American electricity industry's ability to meet the objectives of the Kyoto protocol. However, few capital vintage models exist to explore the degree and speed of potential energy efficiency improvements in the light of capital inertia—the kind of efficiency potentials that are so often identified in bottom-up engineering studies, and inertia which are frequently treated as outside those engineering explorations.

3. Dynamics of the US steel industry

Among the most notable changes that occurred in the US iron and steel industry since World War II are the transition from open hearth to basic oxygen and electric arc furnaces and the use of continuous casting methods instead of ingots (Ross, 1987; Adams, 1995; Ruth, 1995). Further changes are expected as product quality from electric arc furnaces continues to improve and as newer technologies such as direct reduced iron provide increasingly cost-effective alternatives to the energy intensive basic oxygen route (Worrell and Moore, 1997). Also of importance for the industry's energy and emissions profile has been the near doubling in capacity utilization that occurred since the early 1980s (Margolis and Sousa, 1997). Steel furnaces with higher capacity utilization have lower heat loss per ton of furnace charge and thus higher energy efficiencies and lower emissions per ton of product.

Until recently, the majority of US steel was produced in open hearth and basic oxygen furnaces. To produce steel with these technologies requires smelting and refining of iron ores in blast furnaces, and using coal and coke as the predominant energy sources and reduction agents. Production of steel by the open-hearth process discontinued in 1992, mainly in response to tighter air-quality standards. Capacity changes and plant closures can be also attributed to the geographical distribution of demand and import penetration (Beeson and Giarratani, 1997).

The remaining basic oxygen furnaces are typically part of vertically integrated operations that produce ores, a variety of intermediate products such as coke and pig iron, and raw and finished steels. No new capacity has been added since the 1960s in vertically integrated mills (Barnett and Crandall, 1986), capacity fell by over 50% (Ahlbrandt et al., 1996), and no new future capacity additions are expected (Barnett and Kopfle, 1994). Concomitant with these trends, the share of output from electric arc furnaces has steadily increased since the 1970s (Fig. 1). Electric arc furnaces use scrap as

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[1] Many of these assumptions can readily be changed to explore alternative scenarios for the iron and steel industry. For a copy of an interactive version of the model and software, and thus an ability to explore a wider range of assumptions than presented here, send email to: mr217@umail.umd.edu.

their primary material input, which is molten with the use of electric current, and typically operate at smaller scales than vertically integrated mills.

4. Model structure and workings

To investigate the implications of climate change policies for carbon emissions by the industry, we developed a model that uses econometric forecasting techniques in combination with a reduced-form, partial-equilibrium approach to establish industry-wide demand, production, capital investment, capacity levels, expansion and contraction of individual sectors of the industry, and their associated energy use and carbon emissions (Diagram 1). Each of the components of the model is described in more detail below.

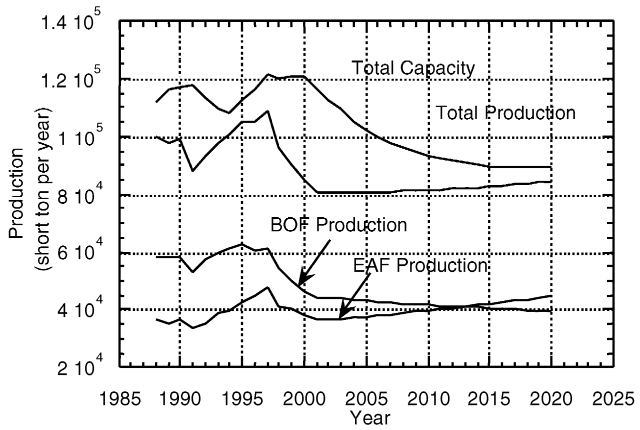

Fig. 1. Base scenario US steel production forecasts by process and total.

Parameters that guide the relationships between variables within or between sub-modules are either econometrically estimated from time series data or based on engineering information. Estimation techniques include multivariate regressions using both simultaneous and lagged independent variables. Model (parameter) specification is based on conventional hypothesis tests (*t*, *F*-test and R^2) as well as extensive econometric diagnostics such as the Lagrange multiplier tests for heteroscedasticity (Breusch and Pagan, 1979) and serial correlation (Godfrey, 1978). For a listing of key equation parameters and test statistics, see Tables 1 and 2.

Embedded within the overarching econometric model of market demand, supply and capital investment is a capital vintage module that explicitly accounts for annual capacity additions and retirements, production, utilization rates and efficiencies of each vintage class within the electric arc furnace(EAF) sector of the industry (Diagram 2). Since no capacity additions are likely to be made within the integrated sector, capital stock and energy intensity changes in the basic oxygen–blast furnace route are simply specified as functions of their capacity utilization. The capital vintage structure of the two sectors determine their corresponding energy efficiencies which are then used in calculating the energy use and hence carbon emissions by the industry.

Various model components depicted in Diagrams 1 and 2 interrelate with each other through feedback processes, some of which exhibit time-lags and non-linearities (Ruth and Hannon, 1997). Their interrelationships over historic time (1970–1997) and

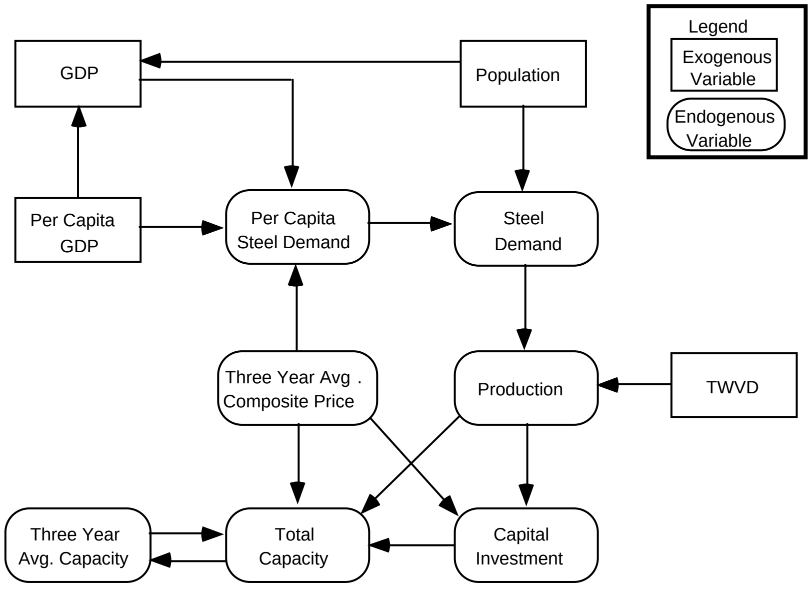

Diagram 1. Aggregate steel industry model components.

Table 1
Regression results for vintage steel model (t-statistics in parentheses)

		Dependent variable				
Regressors	Function form and lags	Per capita steel consumption (Log)	US steel production	Share of EAF log(share/0.8-share)	Investment (Log)	Capacity (Log)
Constant		6.68 (3.99)	55940.91 (3.73)	−3.3468 (−7.06)		
Real GDP per person	$(t-3)$	−0.00014 (−4.78)				
Real GDP		0.00023 (2.92)				
Three-year average composite price of steel	Log	−1.7518 (−3.43)			−0.1549 (-4.59)	0.6997 (17.92)
US steel demand			0.77316 (15.06)			
Trade weighted value of dollar			−468.85 (−4.26)			
(Electricity price-PEP)/ electricity price) ($/E6 BTU)[a]	$(t-3)$			2.0663 (−4.18)		
US cumulative steel production	Log			1.0522 (14.11)		
US steel production	Log $(t-2)$				0.9944 (14.23)	0.2008 (2.6810)
Capital investment	$(t-1)$					6.8485 (3.2529)
LMχ^2 [b]		0.9834 (.3217)	0.1428 (0.7055)	0.2474 (0.6189)	3.03 (0.0817)	2.0071 (0.1566)
LMχ^2 (1)[c]		7.1082 (.2127)	0.9903 (0.9113)	1.6050 (0.6583)	5.04 (.0803)	4.5872 (0.3323)
Adjusted R^2		0.78	0.97	0.98	0.67	0.96

[a] PEP: Primary energy price is a nonweighted average of primary energy prices.

[b] Lagrange multiplier estimate of hederoscedasticity (Godfrey, 1978); significance level in parentheses.

[c] Lagrange multiplier estimate of serial correlation Breusch and Pagan, 1979); significance level in parentheses.

Table 2
Summary of regression results (t-statistics in parentheses)

		Dependent variables			
Regressors	Function form and lags	Coal use efficieny in coke ovens log (ton/ton)	BF coal (% of total BTU in BF)[a]	BF fuel oil (% of total BTU in BF)[a]	Electricity self-generated
Constant		−0.8521 (−4.77)	17.4311 (7.69)	24.5848 (11.31)	1.5433 (2.652)
Coke production rate	Log	0.0543 (5.63)			
Cumulative blast furnace production	Log (t)		−0.2096 (−4.94)		
Coal price ($/million BTU)	$(t-3)$				
Coal price/PEP[b]	$(t-1)$		−10.1019 (−6.18)		
Fuel oil price ($/million BTU)	$(t-2)$			−2.9226 (−5.09)	
EAF share (% of total steel)[c]	(t)				10.4117 (4.90)
LMχ^2 (1)[d]		1.7328 (0.1880)	0.6111 (0.4343)	0.7305 (0.3927)	0.1042 (0.7468)
LMχ^2 [e]		3.9452 (0.1391)	2.2024 (0.5315)	0.9256 (0.62951)	3.5479 (0.1696)
Adjusted R^2		0.88	0.75	0.73	0.86

[a] BF: Blast Furnace.

[b] PEP: Primary energy price is a nonweighted average of primary energy prices.

[c] EAF: Electric Arc Furnace.

[d] Lagrange multiplier estimate of serial correlation Breusch and Pagan, 1979); significance level in parentheses.

[e] Lagrange multiplier estimate of heteroscedasticity Godfrey, 1978); significance level in parentheses.

up to the year 2020 are based on the following key assumptions:

- *Steel Demand*: Per capita steel demand is econometrically estimated as a function of per capita GDP (US Bureau of Census 1999, US Department of Commerce, various years) lagged by three years, GDP in the current year and the average composite price of steel products (New Steel magazine, various years) over the past three years, deflated with a producer price index (PPI) for SIC 3312 provided by the US Bureau of Labor Statistics (1999) (Table 1).

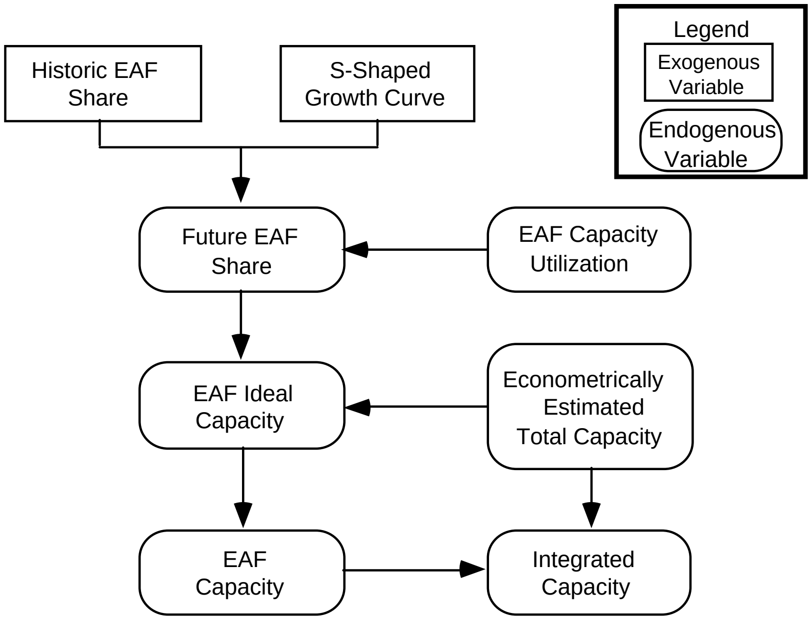

Diagram 2. EAF and integrated capacity.

Once steel demand is calculated on a per capita basis, it is then multiplied by the US population forecast (US Bureau of the Census, 1999) to estimate the total US annual demand for raw steel. The model assumes a constant price after 1998, and assumptions which can readily be justified by the historically flat price trend.

- *Steel Production*: US steel production is calculated as a function of US steel demand and the trade-weighed value of the dollar (TWVD) (Federal Reserve Bank, 1999), which is an index of the value of the dollar relative to the currencies of many of America's trading partners. Historical data of production rates come from the American Iron and Steel Institute (various years). For the results reported below, the TWVD is held constant after 1998 because its historically erratic trend makes sufficiently accurate forecasting virtually impossible.
- *Industry Structure*: Expansion in the share of electric arc production is specified in the model as a function of the relative price of electricity to the primary energy price (PEP) and cumulative electric arc furnace production (Table 1). Cumulative production is defined as an index set to 1 for the initial year of the respective time series. It is used as an indicator of experience (Yelle, 1979; Ruth, 1993). The specification for the base case of the model assumes a maximum production share of 80% for EAF output and an S-shaped asymptotic approach towards that maximum.Higher primary energy prices relative to electricity prices are assumed to make the basic oxygen route for steel production comparatively less attractive than electric arc furnaces, and thus boost EAF production. Long-run output shares, however, are not significantly impacted by market factors. This result is consistent with the findings of Labson and Gooday (1994) who use a growth model to investigate the diffusion of electric arc technology.

  Steel that is not produced by electric arc furnaces enters the economy via the basic oxygen route, requiring blast furnace operations, and thus fossil fuels as the predominant energy source. Little energy is required in basic oxygen furnaces as the reactions are exothermic (Chapman and Roberts, 1983; Szargut et al., 1988). Rather, the bulk of energy requirements for the basic oxygen route is associated with reducing iron oxides in blast furnaces to pig iron.
- *Capital Investment*: The steel industry's real capital investment is estimated as a function of steel production rates of two previous years and the average composite price of steel over the last three years (Table 1). Historic data for new capital investment were provided by the National Bureau of Economic Research (NBER, 1999).
- *Ideal Total Capacity*: The model econometrically forecasts an ideal (desired) capacity level (Table 1) as a function of lagged capital investments, the average capacity during the last three years and lagged production rates (Iron and Steelmaker Magazine, various years). The model explains 96% of the variation in the historical total capacity as published by the US Geological Survey (USGS, 1998).

- *Capital Vintage Model of the EAF Sector*: In modeling the size of the EAF capital stock we modified the perpetual inventory method developed by Jorgenson (1996, 1968). The perpetual inventory method describes in discrete time the size of the end-of-year capital stock as a function of gross new capital investments (I_t), existing capital stock (K_{t-1}) and the rate of replacement (μ):

  $$K_t = I_t + (1 - \mu) * K_{t-1}.$$

  Gross new capital investments do not translate immediately into changes in the capital stock. A lag time exists between the transaction of the gross new investment and the actual change in capital (Table 1). This lag time describes the translation of the desired level of change in the capital stock (or the ideal size of the capital stock) into actual changes in the capital stock. In our adaptation of this approach for the US steel industry, information on annual changes in capital stock was used to calculate production capacity, giving an estimate of the age structure of US capacity to produce raw steel in physical units (Eisner, 1965). Parallel to the capital stock's age structure, the model explicitly traces a set of corresponding age-specific efficiencies which, along with capacity utilization and production levels, determine the sector's energy use.
- *Integrated Capacity and Energy Efficiency*: Capacity of integrated mills is assumed to be the difference between total industry capacity and EAF capacity (see Diagram 1). Therefore, the capital stock of integrated firms is modeled as a stock that is assumed to retire at a variable-rate dependent upon capacity utilization rates. The retirement rates are centered on blast furnace and basic oxygen furnace retirement rates documented in the Annual Energy Outlook (EIA, 1998). Similarly, energy efficiency of the blast furnace was modeled using a variable efficiency improvement rate centered around the average annual efficiency improvement since 1970, which was approximately 2% per year. The variability in the energy use per ton of output was influenced by the capacity utilization of the blast furnace. Inefficiencies at lower capacity utilization rates are a result of reduced furnace charge and thus higher heat loss per ton of pig iron.
- *Fuel Mix*: Six energy sources are considered to supply the energy to the basic oxygen-blast furnace route. Two of these—blast furnace gas and coke oven gas—are self-generated by-products of blast furnaces and coke ovens, respectively. Their availability depends on the production rates of these furnaces. Fuel oil, coal, natural gas, and electricity are used in the blast furnace alongside blast furnace and coke oven gas. Fuel oil use has historically been decreasing. Its decline has been driven to a significant extent by changes in its relative price (Table 2). Similarly, the price of coal relative to the average fossil fuel price significantly influences the choice of coal as an energy source. For the specification of pig iron production, the share of energy supplied by natural gas is set as the remainder that is not supplied by the other five energy sources. The regression equations for the other five fuels have been estimated using a Seemingly Unrelated Regression (SUR) model (Zellner, 1962). Use of the SUR model enables the equations to capture inter-fuel substitution by estimating the demand equations for each fuel type simultaneously. The SUR model is estimated by using generalized least squares which takes into account that cross-equation errors may not be zero.
- *Electricity Generation*: In the past, much of the electricity used in the iron and steel industry was self-generated from by-products such as coke oven gas and blast furnace gas. With the increased reliance on electric arc furnaces, and the need for these by-products as energy sources in blast furnaces, self-generation of electricity declined. To properly reflect the industry's fuel requirements and carbon emissions, the model includes a calculation of fuel requirements by the US electricity sector to supply electricity for iron and steel production. The respective module uses actual data and forecasts of fuel mix in the electricity sector that are reported in EIA (1998) up to the year 2020. Additionally, the model includes the option for the electricity sector to become less carbon intensive as the cost of carbon increases. Taking changes in carbon intensity of electricity generation into account when calculating changes in emissions associated with steel production is important because a policy-induced shift towards electric arc-produced steel may appear as drastically curbing emissions while in fact significant emissions do occur elsewhere in the economy to make that switch possible. As the EAF becomes the dominant steel producing sector, estimating the indirect emissions from the electricity sector becomes ever more crucial. The electricity sector's carbon intensity applied in this model for various costs of carbon was provided by the Interlaboratory Working Group on Energy-Efficient and Clean-Energy Technologies (1999).
- *Carbon Emissions*: Carbon emissions from the iron and steel industry are calculated by multiplying the carbon content per Btu of a fuel with the industry's use of the respective fossil fuel (Table 3). For the decarbonization of limestone, we assume an average emission of 0.0205 metric tons of carbon per ton of steel (Gielen, 1997). To avoid double-counting of emissions from fuels, only the carbon content of purchased fuels and the carbon content of fuels used

Table 3
Carbon content of fuels[a]

Fuel type	Metric tons of carbon per billion BTU (1994 value)
Coal	25.61
Coal (electricity generation)	25.71
Natural gas	14.47
Residual fuel oil	21.49
Oil (electricity generation)	19.95
Liquid petroleum gas	17.02
Distillate fuel oil	19.95

[a] Source: Energy Information Administration 1994.

in the rest of the economy for the generation of purchased electricity are taken into account.

5. Market and technology-based climate change policies

Among the most widely debated industrial policies today are market-based climate change policies that increase the cost of carbon, for example, through implementation of carbon taxes or carbon permits. By switching fuels or by using more efficient means of production, firms realize cost savings to the extent to which they avoid the climate change policy-induced financial burdens that come from incurring a tax or requiring purchase of permits, and to the extent to which efficiency improvements reduce their outlays for materials and energy.

In contrast, the implementation of a technology-based climate change policy, such as design and performance goals, enable investment and policy decision-makers to predetermine the abatement level of the policy on new technologies and thereby reduce uncertainty. The model described above includes a relative energy intensity (REI) policy handle which is a performance goal that institutes an energy efficiency criterion for new capacity relative to the existing aggregate energy efficiency of the steel sector. The performance goal establishes that any *new capacity additions* by industry meet specific efficiency requirements that are set by industry or government (or both). Since all future capacity additions are expected to be in the EAF sector, the REI policy handle is only applied to that sector. An REI of 96%, for example, implies that newly implemented capital is 4% more efficient than the weighted average capital in use in EAF production, where the weights are based on the production rates of each individual capital vintage class.

With a model that captures the dynamic capital adjustments, energy use and carbon emissions through time, it is possible to explore what technology performance goals correspond to which levels of cost of carbon charges. The results of such an exploration are presented below.

6. Model results

6.1. Base scenario

For the base scenario of our model, we assume future growth of GDP at an annual rate of 1.9% and a trade-weighted value of the dollar, measured as an index, fixed at 100. The former is based on Congressional Budget Office forecasts (Congressional Budget Office, 1998) and has been chosen to be consistent with assumptions used by the Energy Information Administration (EIA, 1998) to forecast energy prices. The latter is the mean value for the years 1970–1998 (Federal Reserve Bank, 1999).

Iron and steel output in the US over the next two decades is expected to be stable, with basic oxygen furnaces experiencing a slow decline in their market share (Fig. 1). At lower production rates of basic oxygen furnaces, fossil fuel use in the industry declines (Fig. 2). Because EAF production expands to make up for reduced basic oxygen production and to meet increasing demand for steel, electricity use slightly increases. Concomitant with the increase in EAF production are technology changes that enable the industry to increase its electricity demand at a rate that is below the rate of production increase. However, since much of the electricity is produced from fossil fuels, particularly coal, total carbon emissions from the industry decline at about the same rate as total energy use (Fig. 3).

We project that total emissions in the year 2020 will be approximately 24% below those in 1999. The overall decline of emissions will not be as sharp as in the 1990s because those emissions reductions were in part due to rising capacity utilization rates into the 90% range which increased efficiency levels. The higher capacity utilization rates are a result of the closure of older more

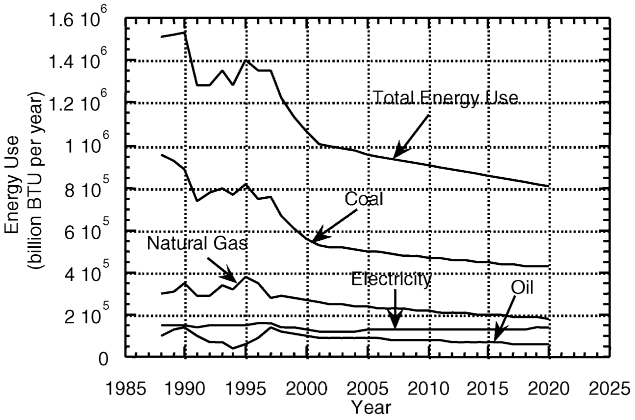

Fig. 2. Base scenario energy use.

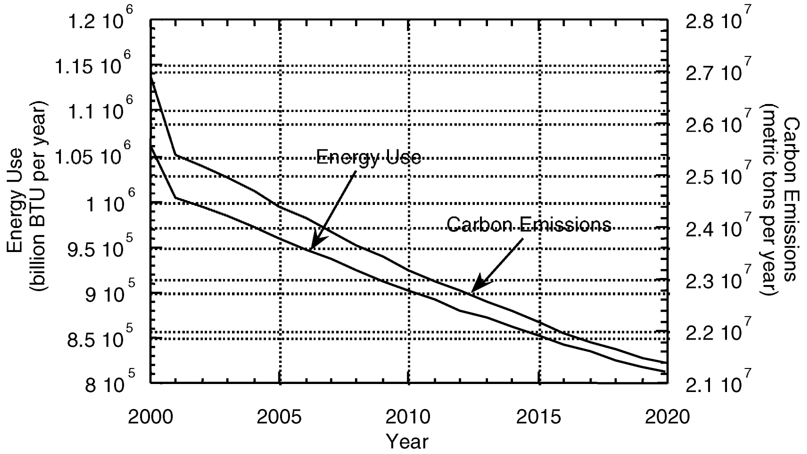

Fig. 3. Base scenario energy use and carbon emissions.

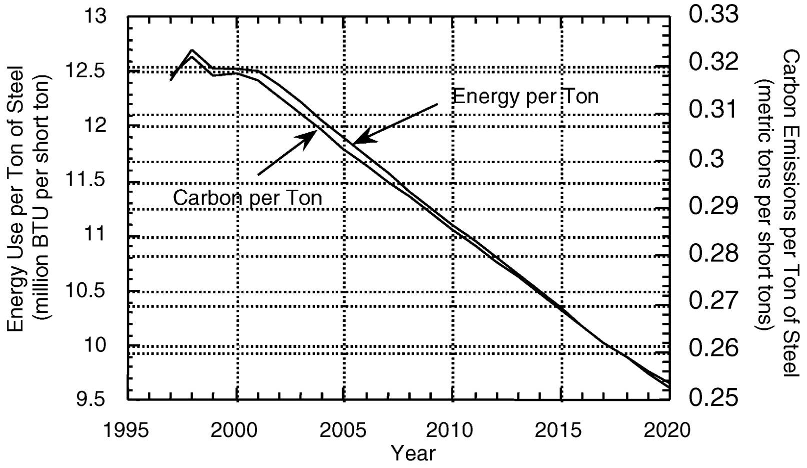

Fig. 4. Base scenario energy use and carbon emissions per ton of steel.

inefficient facilities coupled with the recent increase in production. The industry is expected to operate at continued high capacity utilization rates, and thus further improvements increasingly depend on continued shift to the EAF production route and implementation of newer technologies such as advanced ladling methods or computerized probes.

The share of EAF production is expected to increase to around 53% by 2020 from its present share of 43%. As electric arc furnaces continue to capture an increased market share, and as total industry production experiences moderate increases over the next three decades, basic oxygen furnace production rates slowly decline. In this scenario, EAF output is not likely to increase to a level at which we need to worry about the adequacy of supply of iron and steel scrap. With the shift in production technologies and efficiencies comes a reduction in carbon emissions from 0.32 metric tons of carbon per ton of steel in 1999 to approximately 0.25 metric tons per ton of steel in 2020. Similarly, energy use per ton of output will also decline, from 12.5 million Btu per ton of raw steel to 9.6 million. Carbon emission and energy use profiles per ton of product are shown in Fig. 4.

6.2. Alternative climate change policy scenarios

To investigate the impacts that market-based and technology-led climate change policies would have on energy use profiles and carbon emissions of the industry, we assume that the policies would have been implemented in the year 2000. Costs of carbon of \$25, \$50 and \$75 per ton of carbon were selected to coincide with the costs of carbon commonly referred to in the climate change policy debate. To better compare market-based with technology-based policies, relative energy intensities of electric arc furnaces were found that would generate the same gross carbon emissions in 2020 as with the various cost of carbon levels. The corresponding rates were found to lower the REI of new electric arc furnaces from the base scenario level by 8.8%, 20.2% and 33.4%, respectively (Table 4).

Table 4
Policies producing equivalent amount of carbon emissions when applied over the period 2000–2020

Carbon emission level in 2020 (metric tons)	Cost of carbon policy	Relative energy intensity (REI) policy	Combination cost of carbon and REI policy
21,363,070	$0	0.96	
20,599,098	$25	0.872	
19,705,200	$50	0.758	$25 & 0.853
18,796,079	$75	0.626	$25 & 0.729

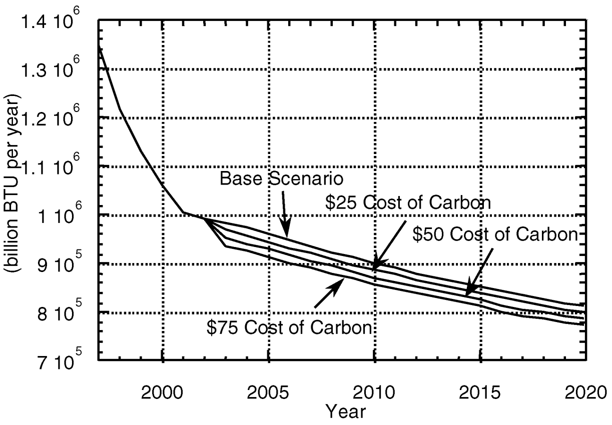

Fig. 5. Energy use under various cost of carbon scenarios.

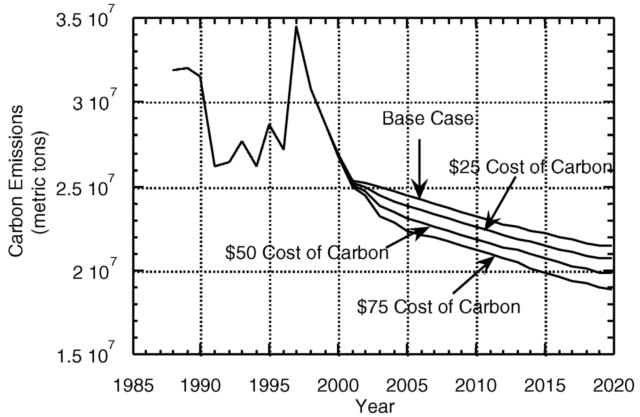

Fig. 6. Carbon emissions under various cost of carbon scenarios.

The introduction of costs of carbon causes a reduction in industry energy use (Fig. 5) and significant decreases in carbon emissions (Fig. 6). Increases in the cost of carbon provide incentive for industry not only to decrease its energy use but also to change its fuel mix. That change in fuel mix occurs to a significant extent as industry supplants basic oxygen with EAF production. The share of EAF production in 2020 will be 55%, 57% and 59% for the $25, $50 and $75 per ton cost of carbon, respectively (Fig. 7).

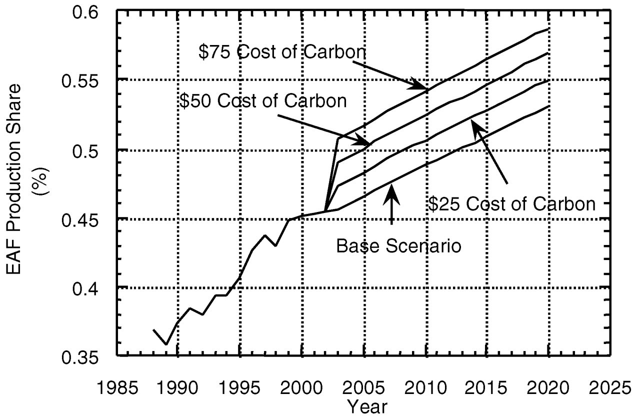

Fig. 7. EAF share of production under various cost of carbon scenarios.

The increased share of production by electric arc furnaces has a marked effect on total carbon emissions and carbon emissions per ton of output. As EAF production is expanded, a shift towards cleaner processes takes place. Sharp declines in blast furnace production, in turn, are associated with higher energy requirements and carbon emissions per ton of product. If furnaces are operated at a lower capacity, heat loss per ton of furnace charge is high, and thus efficiency is low. That furnaces are operated at low output rates during a recession simply to minimize disruptions that come from temporarily closing operations and starting them up again after a recession has been observed by Boyd et al. (1993) on the basis of firm-level data. Since the policy-induced increase in cost of carbon introduced in the model is not temporary, but held at a fixed rate throughout the 2000–2020 period, adjustments continue to take place in the industry. However, the drastic shift away from the basic oxygen-blast furnace route results in lower production rates and thus larger energy requirements per ton of blast furnace steel (Fig. 8). The implementation of a performance goal on new EAF capacity lowers the sector's energy use per ton of steel (Fig. 9). However, large REI reductions are needed to generate the same carbon emissions level as under the cost of carbon policy (Table 4) because performance goals, by themselves, do little to encourage a shift in production to the already energy efficient electric arc sector.

As expected, a simultaneous introduction of cost of carbon and performance goal policies encourage a shift in production to the EAF sector (Fig. 10) and at the same time ensures that the EAF sector will continue energy efficiency improvements. The combined policies consist of a $25 cost of carbon and REI of new EAF capacity such that they correspond with the carbon emissions level in 2020 as the $50 and $75 cost of carbon scenarios. The resultant combinations of $25 cost of carbon and a REI of new EAF capacity are listed in Table 4.

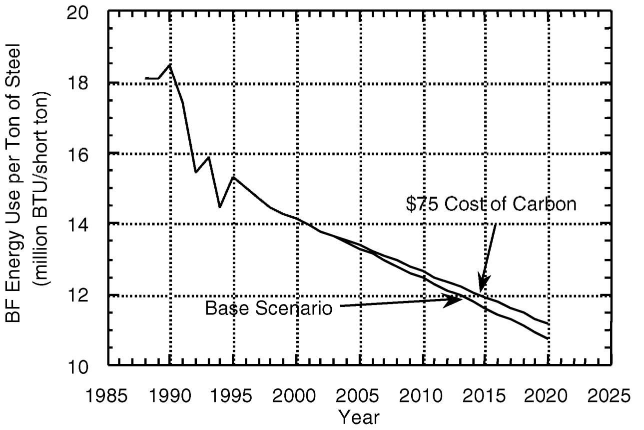

Fig. 8. BF energy use per ton of steel under various cost of carbon scenarios.

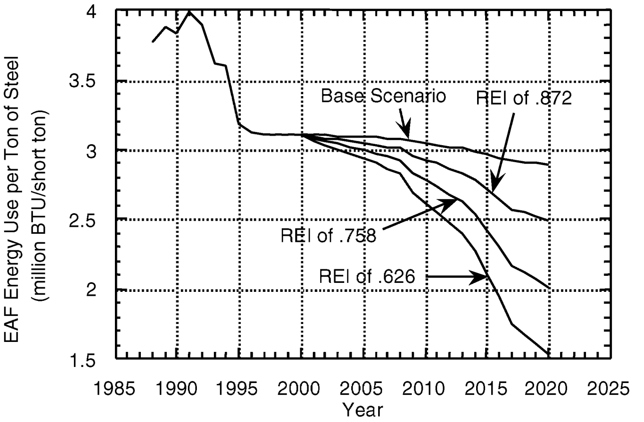

Fig. 9. EAF energy use per ton of steel under various REI scenarios.

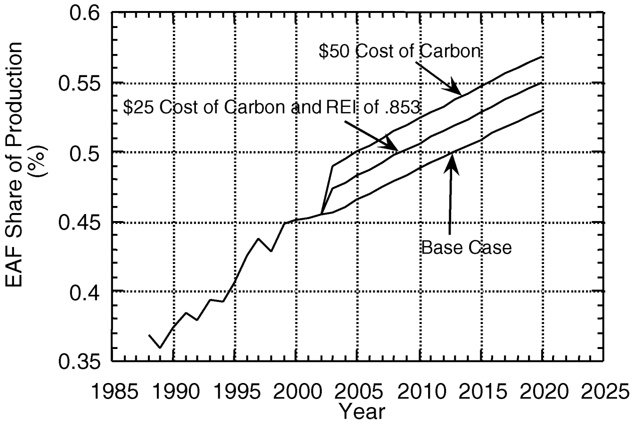

Fig. 10. EAF share of capacity under various scenarios.

7. Discussion

Market-based climate change policies that increase cost of carbon, and performance goals that directly address industrial energy efficiency, have frequently been promoted as means to stimulate industrial emissions reductions. In this context, analysis of the US iron and steel industry shows that implementation of these instruments alters technology mix, energy profiles and emissions in the industry.

Although the industry has vastly improved its energy efficiency and is likely to continue to do so in the future, climate change policies will encourage further increases in efficiency and, under market-based policy scenarios, further increase production by the EAF route. Resulting emissions reductions from cost of carbon increases are more significant than from technology-based policies because cost of carbon policies are more effective in fostering transition to electric arc production. Concomitant reductions in output from blast furnaces are likely to reduce blast furnace capacity utilization. The resultant reductions in blast furnace efficiencies, however, are outweighed by increased efficiency of electric arc furnaces. A consequence of these changes is the further decline in output from the blast furnace-basic oxygen route, which may lead to greater inefficiencies, higher energy costs and eventually higher product costs. Higher product costs, which are not explicitly modeled here, may exacerbate the production shift to an even greater extent. To remain competitive, the traditional integrated sector, in which the majority of steel industry workers are employed, must continue to foster technological advancements, close older facilities, and sharpen focus on high-end steel products.

The results of the model further indicate the importance of examining the capital structure of the industry. Implementing performance goals in the US iron and steel industry with its long-lived capital, slow turnover rates and relatively stagnant or declining production rates can only have a significant impact on long-term energy use if the performance goals are highly ambitious. Realizing ambitious performance goals may require significant research and development efforts as well as incentives for rapid technology adoption. Policies that are able to shift production between existing production technologies and change fuel mix dynamics are more effective. Future research is needed to assess the investment costs to meet performance goals. These costs can then be compared with potential savings that would accrue, for example from investing in new, more efficient capacity and retirement of existing capital instead of paying a carbon tax or purchasing carbon permits. Such comparisons can be used to identify policies desirable from the industry's perspective.

The following three main messages derive from the discussions above. First, in order to assess climate change policy impacts on the US iron and steel industry requires explicit consideration of the dynamics that describe production shares, technology change and fuel choice by the different sectors of the industry. Second, the responses of individual establishments will vary between blast furnace, basic oxygen and electric arc producers and the associated vintage structures and turnover rates of their capital stocks. Effectiveness of the policies depends to a large part on the technical details of the production processes, as the example of efficiency declines with lower furnace charge illustrates. Therefore, these technical issues need to be taken into account in the choice among policies. Third, the results cannot be construed to unequivocally endorse market-based climate change policies for all industries. For example, similar analyses for the US pulp and paper and the US ethylene industries showed that technology-led climate change policies are more effective in reducing carbon emissions than cost of carbon policies (Ruth et al., 2000a, b, 2001a). The most effective policy will depend on industry-specific features, such as its capital vintage structure and turnover rates, features that to date have found little recognition in analyses of climate change policies.

Acknowledgements

This project was made possible by the support from US Environmental Protection Agency under Grant Number X 826822-01-0 and benefited from many discussions with John “Skip” Laitner, Brynhildur Davidsdottir, members of the US Department of Energy and representatives from the US iron and steel industry. However, the paper does not necessarily reflect the views of US EPA or US DOE nor those of the individuals who provided input into, or commented on, the model on which this paper is based.

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